Article

Successful Tests on Detecting Pre-Earthquake Magnetic Field Signals from Space

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Abstract: Earthquake prediction is the holy grail of seismology and one of humanity’s greatest dreams. The Earth’s magnetic field appears to be one of the best possible precursors of earthquakes, although the topic is controversial. Recent advancements have made it possible to observe magnetic fields from satellites with great accuracy. We utilize magnetic measurements from Swarm satellites to explore the potential identification of anomalous magnetic signals preceding earthquakes. Focusing on 1077 major earthquakes that occurred in 2014–2023 in the Alpine–Himalayan belt, we apply an automatic algorithm to data recorded 10 days before each earthquake. This analysis reveals clear pre-earthquake anomalies in the magnetic field components. Notably, a robust correlation is established between the duration of these anomalies and the earthquake magnitude, indicating that as the earthquake magnitude increases, so does the duration of the anomaly. Here we show that this method has a great ability to make predictions (high accuracy 79%, precision 88%, F1-score and hit rate 84%), thus becoming the basis for an Operational Earthquake Prediction System (OEPS).

Keywords: earthquake; precursor; satellite data; anomalous; magnetic field

1. Introduction

Earthquakes can be caused by a variety of natural and human-induced processes. In this paper, we deal with earthquakes caused by natural processes. Their causes include the following: (1) Plate tectonics, as earthquakes can occur where (a) tectonic plates separate and are known as divergent boundaries, such as mid-ocean ridges, (b) along convergent boundaries where tectonic plates collide, which often produce the strongest quakes; and (c) along transform boundaries where plates slide horizontally past each other; (2) Faulting, which includes (a) normal faults where tensile forces cause the crust to break, (b) reverse faults in which compressive forces shorten and thicken the crust, and (c) strike-slip faults in which lateral shear forces cause horizontal displacement; (3) Volcanic activities occur due to the movement of magma inside the Earth, which exerts pressure on the surrounding rocks and can cause them to fracture, causing some earthquakes to occur; (4) Rifting and continental drift that cause stress accumulation and earthquakes, especially in areas where the continents are separating; and (5) Intraplate earthquakes that occur far from the plate boundary, usually due to the reactivation of ancient faults in a tectonic plane. All these phenomena involve a preparatory process where stress is applied and strain accumulates in the lithosphere over time. This phase, known as the earthquake preparation, leads to various physical changes in the environment known as earthquake precursors [1–3]. Detecting and identifying these precursors are crucial for studying and potentially predicting earthquakes. Research in earthquake precursors has revealed anomalies in the geomagnetic field and total electron content near the epicenter as potential indicators. While some precursors are observed near the epicenter, others can be detected in the magnetic conjugate zone [4]. Efforts have been made to monitor and analyze earthquake
preparation using ground [5–10] and satellite data [11–13]. Satellites specifically designed for magnetic field measurements, such as CHAMP and Swarm, have been instrumental in observing electromagnetic phenomena likely associated with earthquakes [14,15]. Magnetic field anomalies have been linked to changes in rock properties due to stress, and their detection has been reported before major earthquakes [16,17].

The term “earthquake precursor” encompasses a range of physical phenomena that occur prior to certain earthquakes and are expected to be physically related to their preparation. Various precursors, such as electric and magnetic fields, changes in water levels, gas emissions, temperature fluctuations, surface alterations, and seismic patterns, have been identified [9,10,18–21]. However, not all precursors manifest in every earthquake, posing challenges to their reliability. Researchers from different disciplines have contributed to identifying and understanding these phenomena, but issues of reproducibility and verification still remain. Magnetic field changes have emerged as significant earthquake precursors, and advancements in remote sensing and satellite technology have furthered their study. Early works in the 1960s explored electromagnetic signals associated with seismic events, and subsequent studies confirmed distinct magnetic field anomalies related to earthquakes [6,22–24]. Both ground and satellite data have been analyzed to detect magnetic anomalies potentially caused by seismic events. Laboratory and field trials have supported the connection between seismic events and magnetic field changes, attributed to variations in rock properties [25,26]. Satellite data, including observations from missions like DEMETER, CHAMP, and Swarm, have contributed to the identification of magnetic anomalies preceding earthquakes [14–16]. Models have been proposed to explain the interconnectedness of the lithosphere, atmosphere, and ionosphere during earthquake preparation. These models suggest processes such as ionization of the atmosphere by positive holes released from the fault surface or the release of gases, like radon, from the lithosphere [19,27–29]. These processes trigger a chain of interactions that extend from the lithosphere to the atmosphere and eventually the ionosphere.

Earthquakes are not randomly distributed but tend to occur along specific belts worldwide. The Alpine–Himalayan belt, the focus of this research, extends for more than 12,000 km from southern Europe to eastern Asia and experiences significant seismic activity, the most intense on the planet, after that of the Pacific Ring of Fire. It is the result of plate collisions, such as the African–Sinai–Arabian plate with the Eurasian Plate in the west and the collision of the Indian continent with Eurasia in the east. The Eurasian Plate, which includes Europe and a large part of Asia, is moving southward. The African Plate is moving northward, pushing against the Eurasian Plate. The Indian Plate is moving northward and colliding with the Eurasian Plate. This belt encompasses several major continental plates, as mentioned, as well as internal seas with oceanic crust. The collision of the African Plate with the Eurasian Plate has caused compression and folding of the Earth’s crust, leading to the formation of the Alps in Europe. Similarly, the collision of the Indian Plate with the Eurasian Plate has resulted in the formation of the Himalayas, the highest mountain range in the world. This system also includes several high plateaus such as Iran, Turkey, Pamir, and Tibet, as well as three inland seas with an oceanic crust, namely the Mediterranean Sea, the Black Sea, and the Caspian Sea. The seismicity in this region (see Figures 1 and S1 for the earthquakes analyzed in this study) is attributed mostly to ongoing continental collisions, with a significant amount of seismic energy released annually (around 100 significant earthquakes/year). Analyzing earthquakes in this belt, specifically those with a magnitude greater than or equal to 5.0, and correlating them with satellite precursory anomalies can provide insights into the relationship between earthquake magnitude and magnetic field anomaly features. Focusing on a specific tectonic belt mitigates the possibility of confusing pre-earthquake related anomalies with anomalies related to other phenomena, although we must admit that some portions of the anomalies cannot be clearly attributed to the preparation of earthquakes. Confutation analysis is performed to assess the validity of the relationships discovered, establishing the base for
an Operational Earthquake Prediction System (OEPS). A few words are here necessary to distinguish between prediction and forecasting.

![Figure 1. Earthquakes used in this study](image)

Figure 1. Earthquakes used in this study. Epicenters of earthquakes with a magnitude (“mag” in the legend inside the figure) greater than or equal to 5.0 that occurred in the Alpine–Himalayan belt (20° ≤ lat ≤ 60° and −20° ≤ long ≤ 100°) from 2014 to 2023 (source: https://www.usgs.gov; accessed on 1 February 2024).

Prediction involves determining the specific time and location where a natural hazard of a given magnitude will occur. Although time, location, and magnitude are given with some uncertainty, the intention would be that they have enough accuracy that meaningful actions, such as evacuations, can be planned and implemented. Forecasting is a broader and less exact approach, offering a probabilistic estimate of a hazard happening. For example, a seismic hazard map in a certain region might state that there is a 25% chance of a magnitude 7.0 earthquake occurring within the next 20 years.

According to the above definitions, the method we propose is closer to a prediction than a forecast. This is the reason we call it OEPS.

Regarding the depth of the seismic events, we performed a simple comparison among the earthquakes with different hypocentral depths and occurring earthquakes: we split the earthquakes according to five classes of depth (30, 60, 90, and 120 km, and deeper hypocenters) and found that the percentages of earthquakes with anomalies were all very similar, ranging from 79 and 85%, with the highest percentage for the deepest class. Therefore, we finally decided to include all earthquakes in our analysis, independently of their depth.

2. Materials and Methods

2.1. Swarm Satellite Observations Data

In this study, to investigate magnetic field anomalies possibly caused by earthquakes that happened in the Alpine–Himalayan belt, we used Swarm satellite data. Swarm is a three-satellite mission of the European Space Agency that was launched and placed into a quasi-polar orbit in late 2013 to study the Earth’s magnetic field [30].

Two of the satellites, namely Alpha (SW-A) and Charlie (SW-C), fly side by side in a low orbit with an altitude of nearly 450 km, while the third satellite, Bravo (SW-B), is in a higher orbit of about 510 km. This particular orbital configuration was chosen to achieve various scientific aims: for example, the lateral flight of two satellites, Alpha and Charlie, can lead to the measurement of aligned field currents flowing in the radial direction [31]. The Alpha and Charlie satellites fly close together, and the east–west separation of the orbits of these two satellites is approximately 1.4 degrees, and their inclination angle in polar orbits reaches 87.4 degrees. Also, their height is a significant parameter because it was chosen to develop
the mission as long as possible. In this way, it will be feasible to monitor the geomagnetic field for a complete solar cycle (11 years), which is very important because solar activity has one of the most significant effects on the geomagnetic field. The three satellites are identical, so each satellite is equipped with the same advanced magnetometers providing high-precision and high-resolution measurements of directional strength and magnetic field variation, supplemented by electric field and plasma parameters measurements, accelerometers, and accurate orientation. These observations are presented as level 1-b data, which are calibrated and formatted in time series.

The research targets assigned to this mission are as follows: (1) studies of core dynamics, geodynamic processes, and mantle-core interaction; (2) mapping the polarization of the lithosphere and its geological interpretation; (3) determining the 3D electrical conductivity of the mantle; and (4) investigating the electric currents that flow in the magnetosphere and ionosphere. However, a challenging part is to separate the different sources in the core, lithosphere, ionosphere, magnetosphere, etc., to obtain the total measured magnetic field [32]. Some of the principal results obtained so far by the Swarm satellite mission are as follows: a map of the magnetic field of the lithosphere with a high resolution of 250 km [33], and the effect of ocean tides on the geomagnetic field and electromagnetic induction produced by ocean circulation [34,35].

In this study, we use magnetic field vector components and total intensity with a low rate of 1 s sampling and level 1-b to analyze the magnetic field as observed by the lower orbit satellites, i.e., SW-A and SW-C. De Santis et al. [36] performed a worldwide systematic correlation analysis using about 5 years of magnetic field Swarm satellite data and earthquakes. One of their main results was to confirm the Rikitake law [37], which states the anticipation time of the appearance of the earlier precursors from satellite depends on the earthquake magnitude: the larger the magnitude, the longer the anticipation time of the earlier precursor. This time represents the beginning of the appearance of the studied precursor, which then will continue to appear sporadically up to the approaching of the earthquake. We prefer here to consider the same shorter interval of time before the earthquake occurrence for all earthquakes, in order to avoid the possible interference of other earthquakes close to the earthquake of interest. This choice has also another advantage, i.e., that of speeding up the analysis very much [36]. The data used for the analysis are from ten days before the earthquake until the day of the event and along the routes that pass through the Dobrovolsky region, as a proxy of the earthquake preparation area [38]. This choice to analyze ten days before each earthquake is also supported by the results of previous research (e.g., [37,39]), which state most magnetic satellite anomalies can be found within 5–10 days prior to an earthquake. The Dobrovolsky region is a circular area centered at the earthquake epicenter, calculated by the following equation,

\[ R = 10^{0.43M} \]

where \( R \) is the radius of the area from the epicenter in kilometers and \( M \) is the magnitude (we generally consider moment magnitude, \( M_w \) when it is available) of the earthquake [38]. According to various studies, most of the precursor phenomena have been observed inside this area [40,41]. Its use also for data at ionospheric altitudes is justified because when the Dobrovolsky region is extrapolated at those altitudes, the Dobrovolsky radius is only 7% larger than at the Earth’s surface. The direct use of the Dobrovolsky radius given for the Earth’s surface is thus not only more straightforward but also conservative.

Regarding the quasi-polar orbit of the Swarm satellites, we have preliminarily considered the impact of the Swarm satellites’ orbit evolution on our results. The evolution of the Swarm constellation and its orbit could indeed affect the spatial and temporal resolution of the data, which in turn might influence the detection and characterization of magnetic anomalies. We have taken into account these potential variations by cross-referencing data from multiple satellite passes and ensuring that the anomalies are consistent across different orbits. Indeed, our approach helps to mitigate the impact of any single orbit’s evolution on our overall findings.
2.2. Seismic Data

Catalogs of earthquakes that have occurred and include earthquake source parameters such as origin time, epicenter, magnitude, etc., are the principal source for various earthquake studies undertaken by national and international agencies. For this study, we use the data extracted from the United States Geological Survey (USGS) (https://www.usgs.gov) because it is considered complete worldwide above magnitude $M = 4.5–5.0$.

We downloaded data on the earthquakes that occurred in the interval from 1 January 2014 to 7 December 2023 in the Alpine–Himalayan belt with magnitude $M \geq 5.0$. Data on a total of 1077 earthquakes were obtained. Among these, 882 cases have magnitudes between 5.0 and 5.5, 132 events have magnitudes between 5.5 and 6, and 63 events have magnitudes greater than 6.0. The epicenters of the earthquakes are shown in Figure 1. Table S1 of the Supplementary Material contains the list of all earthquakes with specific information such as earthquake numbers, dates, latitudes, longitudes, depths, and the magnitudes of the earthquakes. In Figure S1, the histogram shows the distribution of earthquakes’ magnitude (please note that with the initial S, we indicate the figures in the Supplementary Material).

2.3. Analysis and Magnetic Field Satellite Anomaly Definition

In this analysis, all magnetic field X (north), Y (east), Z (vertical), and total intensity $F$ measurements (in the figures, the components are also indicated as $B_x$, $B_y$, and $B_z$) with a 1 Hz sampling rate and level 1-b are used. As a first step and according to the magnitude of each earthquake, the magnetic field vector data were downloaded from the Swarm satellite website (https://earth.esa.int/eogateway/missions/swarm/data (accessed on 2 July 2024)). The area of interest for data preparation for each event was estimated in the Dobrovolsky area, i.e., using Equation (1).

For each earthquake, all the satellite orbits that crossed the Dobrovolsky region from 10 days before the earthquake to the day of its occurrence are analyzed. First, we obtain the first-time derivative of each path. This operation removes most of the slow fluctuations of the magnetic signal. A best-fit curve, adjusted using the cubic-spline algorithm with 6 s node points, is applied to the tracks and subtracted from the time series. The resulting residuals are plotted and then analyzed. The scale is kept constant within a range of $\pm 2 \, \text{nT}$ to facilitate the comparison of residuals across different tracks. These residuals are highly sensitive to any sudden change in the original signal [42].

Once we obtained the residuals, a conventional automatic algorithm usually applied in seismology was here used to detect magnetic anomalies. The most widely utilized algorithm in weak-motion seismology is the “short-time-average through long-time-average trigger” ($\text{STA/LTA}$; e.g., [43]). This algorithm continuously calculates the average absolute amplitude of a seismic signal within two consecutive moving-time windows. The short time window ($\text{STA}$) is sensitive to seismic events, while the long-time window ($\text{LTA}$) provides information about the temporal amplitude of seismic noise at the specific site. An event is considered “declared” when the ratio between the two exceeds a predetermined value. In this study, we employed this algorithm to identify anomalies in the magnetic field vector. Specifically, we used an $\text{LTA}$ of 50 s and an $\text{STA}$ of 5 s, and set the pre-set $\text{STA/LTA}$ value to 3. After identifying orbits displaying magnetic anomalies, we employed the $\text{STA/LTA}$ algorithm to assess the length of these anomalies. In the subsequent step, we estimated the duration of the time windows containing anomalies and calculated the ratio of the anomaly’s energy to that of the entire time series. Additionally, we considered the signal-to-noise ratio to account for data quality and the anomalies identified. To calculate the signal-to-noise ratio, we divided the mean squared amplitude of the anomaly by the mean squared amplitude of the entire signal.

Finally, we examined the resulting designs to identify obvious anomalies with the following characteristics [42]:

1. The peak-to-peak amplitude is $\geq 0.3 \, \text{nT}$.
2. Anomalies should last for at least ten seconds.
3. Determine if the anomalies did or did not occur during times when geomagnetic indicators were in quiet conditions.

Ionospheric parameters are influenced by solar activities. Geomagnetic indices such as Kp, Dst, and F10.7 are measured to quantify the level of solar activity. Usually, geomagnetic perturbations have less penetration in middle latitudes. The criterion of the quietness of geomagnetic indices is usually (F10.7 \( \leq 150 \), Kp \( \leq 3 \), |Dst| \( \leq 20 \) nT) [44,45]. The data related to geomagnetic indices are provided to the user through the Swarm satellite itself and also through the sites https://www.ncei.noaa.gov/products/space-weather and https://wdc.kugi.kyoto-u.ac.jp/ (accessed on 2 July 2024). As a result, Kp, Dst, and F10.7 indices were investigated to evaluate the difference between potential seismo-ionospheric disturbances and solar geomagnetic disturbances.

The major difference between ionospheric effects caused by geomagnetic storms and potential seismic effects is that, given a certain time of observation, the former have a global effect and are observed worldwide, while the latter are only observed near the epicenter, so are rather local [46].

3. Results and Discussion

In this research, all Swarm satellite level 1-b data of the magnetic field components with a sampling rate of 1 Hz obtained from Alpha (SW-A) and Charlie (SW-C) satellites from the 10 days preceding Mw5.0+ earthquakes occurring from 2014 to 2023 in the Alpine–Himalayan seismic belt have been investigated. We restrict the investigation to just 10 days before earthquakes because we want to focus on the last short-term phase of the earthquake preparation, although we recognize that precursors can appear much earlier [36,37,47]. After applying the automatic algorithm of detection to the database among all the earthquakes (1077 earthquakes), magnetic anomalies were identified in 900 events. Table 1 shows the number of earthquakes present in different magnitude ranges, and from this number, how many earthquakes have at least one orbit containing magnetic anomalies. The statistics presented in Table 1 are for the general case and do not take into account the status of geomagnetic indices. When we consider only satellite data detected during the quiet state of the ionosphere, so excluding those orbits with high geomagnetic indices, the number of examined earthquakes reduces to 786 (Table 2). Out of this total, 615 earthquakes have at least one orbit with magnetic anomalies. Earthquakes that have not shown any magnetic precursor signals mostly have lower magnitudes, i.e., between 5 and 5.5. Indeed, this could be due to the lower energy associated with this type of earthquake and the sensitivity of the sensors on the satellites. According to the obtained results, it can be said that most anomalies are observed in the Y component of the magnetic field [36,48]. In a few cases, anomalies have also been observed in the X and Z components of the magnetic field, which frequently occurred in faults with oblique and reverse mechanisms. Of course, this issue needs further investigation, which is outside the scope of the present study.

<table>
<thead>
<tr>
<th>Magnitude Range</th>
<th>Number of EQs That Exhibit Anomalies</th>
<th>Total Number of EQs</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full range</td>
<td>900</td>
<td>1077</td>
<td>83.5</td>
</tr>
<tr>
<td>5.0–5.5</td>
<td>663</td>
<td>821</td>
<td>80.8</td>
</tr>
<tr>
<td>5.5–6.0</td>
<td>155</td>
<td>172</td>
<td>90</td>
</tr>
<tr>
<td>6.0–6.5</td>
<td>53</td>
<td>55</td>
<td>96</td>
</tr>
<tr>
<td>6.5–7.8</td>
<td>29</td>
<td>29</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 2. Number of earthquakes considering geomagnetic conditions. The ratio of the number of earthquakes that had magnetic anomalies to the total number of earthquakes is calculated for different magnitude ranges and for the entire magnitude range, taking into account quiet geomagnetic conditions.

<table>
<thead>
<tr>
<th>Magnitude Range</th>
<th>Number of EQs That Exhibit Anomalies</th>
<th>Total Number of EQs</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full range</td>
<td>615</td>
<td>786</td>
<td>78.2</td>
</tr>
<tr>
<td>5.0–5.5</td>
<td>448</td>
<td>594</td>
<td>75.4</td>
</tr>
<tr>
<td>5.5–6.0</td>
<td>110</td>
<td>130</td>
<td>84.6</td>
</tr>
<tr>
<td>6.0–6.5</td>
<td>38</td>
<td>43</td>
<td>88.3</td>
</tr>
<tr>
<td>6.5–7.8</td>
<td>19</td>
<td>19</td>
<td>100</td>
</tr>
</tbody>
</table>

From previous research [14,36], we know that the Y component of the magnetic field is usually the least affected by anomalies due to sources outside the lithosphere, such as magnetic storms, and most changes in this component are caused by factors inside the lithosphere. On the other hand, X and Z components are more affected by the anomalies outside the lithosphere [48]. For this reason, more attention has been paid to quiet geomagnetic conditions in the use of X and Z components, and in one case, there is a geomagnetic perturbation, so the anomalies of the X and Z components were not used. Analogous anomalies have been seen in research by other authors. For example, De Santis et al. [16] were able to investigate 12 major earthquakes in a period from 2014 to 2016, and observed a series of anomalies in the magnetic field for each of them. Afterward, using the shift in the cumulative number of anomalies, they attempted to show a variation in the magnetic field before some significant events. However, in the present research, new and more extensive results have been obtained from the analysis of the satellite magnetic field anomalies.

Figure 2 shows that for the Nepal Mw = 7.8 earthquake of 25 April 2015 (Earthquake number 120 as listed in Table S1), there is an obvious precursory anomaly in the Y component of the magnetic field from latitude 25° to 33°, lasting about 120 s. Please note that in the same spatio-temporal interval, another M5+ earthquake occurred, as indicated by a red point. In Figure S2, the Swarm satellite shows a clear anomaly in the Z magnetic field component, lasting 45 s, before the Mw = 6.6 earthquake in Greece (Earthquake number 359 in Table S1). As shown in Figures S3 and S4, respectively, a 26 s lasting anomaly in Y was detected before the Mw = 5.9 earthquake in Iran (Earthquake number 572 in Table S1), and another lasting 15 s occurred before the Mw = 5.5 earthquake in Italy (Earthquake number 914 in Table S1). Notably, among the examples provided, the earthquake with the highest magnitude (Mw = 7.8) generated an anomaly lasting 120 s, while the earthquake with the smallest magnitude (Mw = 5.5) produced an anomaly lasting only 15 s. Intermediate magnitude earthquakes resulted in anomalies with durations falling between these extremes.

The results clearly suggest a correlation between the duration of the anomaly and the magnitude of the earthquake. Other examples are given in Figures S5–S14 of the Supplementary Material. Generally, there is a trend where, as the magnitude of the earthquake increases, the duration of the corresponding satellite-detected anomaly also increases, indicating greater persistence. Similarly, the amplitude of the anomalies follows a similar pattern, increasing with the magnitude of the earthquake.

In summary, the results, along with the figures in the Supplementary Material, lead to the conclusion that earthquakes of different magnitudes consistently produce satellite magnetic field anomalies within specific duration ranges. For instance, earthquakes with a magnitude of Mw = 5.5 typically exhibit anomalies lasting approximately 10 to 20 s, while those with Mw = 7.0 manifest anomalies lasting around 40 to 80 s. This range expands proportionally with increasing magnitude. The amplitude of anomalies also conforms
to this relationship. The maximum and minimum values within these ranges depend on the satellite orbit’s distance from the earthquake epicenter and the timing of anomaly observation. Smaller distances and closer observation times to the event result in more pronounced and longer-lasting anomalies. The observed correlation between anomaly length (i.e., duration), orbital distance, anomaly energy, and earthquake magnitudes has motivated further exploration into the detailed relationships among these parameters.

![Image](image_url)

**Figure 2. Identified magnetic anomalies.** Anomalous event detected on 22 April 2015 by SW-A, which was three days before the 25 April 2015, Mw = 7.8 Nepal earthquake. The anomalous satellite-detected event occurred at a distance of 279 km from the epicenter. The epicenter is indicated by a green star, and a green oval surrounding it (the oval shape is because of the projection; it would be actually a circle over the earth’s surface and at satellite altitude), representing the Dobrovolsky area. The red line illustrates the path of the satellite. At the top of the figure, relevant information is provided, including the satellite name (Alpha = A, Charlie = C), the date and time of the satellite passing through the specified area, the date and time of the earthquake, the satellite track number, geomagnetic indices (Dst, Kp, F10.7), and the closest distance of the orbit from the epicenter of the earthquake. The direction of satellite movement is indicated by a black arrow, with the upward direction represented by an arrow pointing upwards (ascending) and the downward direction represented by an arrow pointing downwards (descending). In this case, the orbit is descending. The red point depicts another M5+ earthquake occurring in the same spatio-temporal interval.

**Magnitude-duration correlation**

According to Figure 3, which is obtained from the detailed analysis, there is a logarithmic relationship between the duration of the magnetic anomaly appearing in the components of the magnetic field (y-axis) and the magnitude of the earthquake, generally as Mw (x-axis). Confidence intervals are marked with thin black lines and mean data are marked with thick black lines. In Figure 3a, all data are used without considering geomagnetic indices. As shown in this figure, the obtained relationship can be expressed as follows:

\[ M = (1.414 \pm 0.771) \times \ln(Du) + (1.29 \pm 0.678) \]  

where \( M \) is the magnitude of the earthquake and \( Du \) is the duration of the anomaly (in seconds). Consequently, the greater the magnitude of the earthquake, the longer the duration of the anomaly. This issue can be seen in Figures 2 and S2–S4, and the other figures in the Supplementary Material.
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Figure 3. Magnitude-duration correlation. The plot illustrates the relationship between the natural logarithm of anomalies duration (y-axis) and the magnitude of earthquakes (x-axis) under different conditions. (a) All the data have been considered without applying any specific conditions. (b) The data are filtered based on quiet geomagnetic conditions, with criteria such as Kp ≤ 3, |Dst| ≤ 20 nT, and F10.7 ≤ 150. (c) The data are filtered based on a signal-to-noise ratio greater than 2. (d) The data are filtered based on a signal-to-noise ratio greater than 5.

In Equation (2), the R-square of the fit is equal to 0.976, which shows that the model can predict the results very well. The corresponding error value is equal to R-mse = 0.125, so comparable to the typical error associated with the magnitude when estimated from seismograms. In Figure 3b, the effect of geomagnetic indices on the relationship is investigated. In this panel, the condition of the geomagnetic indices being in a quiet state has been applied to the data (i.e., all three conditions are checked simultaneously: Kp ≤ 3 AND |Dst| ≤ 20 nT AND F10.7 ≤ 150). As can be seen, the relationship has not changed drastically and has remained stable, and it can be said that the R-square and the error rate have remained almost constant. In two other investigations, anomalies with a signal-to-noise ratio greater than two (Figure 3c) and values greater than five (Figure 3d) have been selected. As evident from the comparison between the results for the general state of the data (Figure 3a) and those with the signal-to-noise ratio selection (Figure 3c,d), it is clear that considering this ratio has further improved the stability of the results, although the coefficients of the relationship do not change significantly.

Magnitude-Energy correlation

Another significant parameter obtained from the results is the identified anomaly energy, En. This “energy” is represented here by the amplitude of the anomaly divided by the average amplitude of the whole half-orbit. As explained earlier, the amplitude of the anomaly is related to the earthquake’s magnitude. As a result, the anomaly energy is also related to the magnitude. According to Figure S5, where the y-axis is the natural logarithm energy and the x-axis is the magnitude, there is a natural logarithmic relationship between the two quantities. In Figure S5a, which is for all data, there is the following relationship between energy En and magnitude M:

\[
M = (1.469 \pm 0.877) \times \ln(En) + (-0.032 \pm 0.758)
\]  

(3)

The R-square of the system is equal to 0.96, which shows the high capability of the model to predict the results, and the error value is equal to 0.167. Here, we also experiment with the obtained relationship using geomagnetic indices (Figure S5b) and a signal-to-noise ratio greater than two and greater than five (Figure S5c,d). In both cases, it can be
observed that the relationship maintains its stability well, and there is not much change in the relationship.

**Magnitude-(Duration × Distance) correlation**

The results of the magnitude-duration correlation indicate a clear pattern: for each distinct magnitude, there exists a range of magnetic anomaly durations. The values within this range are influenced by the distance from the orbit to the earthquake epicenter. In essence, a shorter distance from the orbit to the epicenter corresponds to a longer duration of the observed anomaly, and conversely, a greater distance results in a shorter duration (refer to Figures S9 and S10 for illustrative examples). In Figure S6a, the correlation between the natural logarithm duration of the detected anomaly at a certain distance from the earthquake epicenter (y-axis) and the magnitude $M$ (x-axis) can be clearly demonstrated. This relationship is given as:

$$ M = (0.587 \pm 1.034) \times \ln(Du \times Dist) + (1.022 \pm 1.168) $$  \hspace{1cm} (4)$$

Here $Dist$ is the distance, i.e., the horizontal projected distance of the satellite anomaly with respect to the earthquake epicenter (in km).

The R-square of the system here is equal to 0.99, which shows how robust is the relationship (3) and the consequence of distance on it. The error value in $M$ is equal to 0.074, so it is practically negligible. In Figure S5b, the effect of geomagnetic indices on the system is investigated. Another test was performed on the system (Figure S6c,d), in which the signal-to-noise ratio for values higher than two (Figure S6c) and values higher than five (Figure S6d) is applied to the data. Compared to the general state of the data (Figure S6a), it can be observed that the system has maintained its stability. The error and stability values have changed very little (R-square = 0.98 and R-mse = 0.108).

**Magnitude-(Duration × Time) correlation**

In the discussion of earthquake precursors, in addition to magnitude and distance, another important parameter is the time with respect to the earthquake occurrence. According to the obtained results, the anomalies that are close to the time of the earthquake are clearer and longer. For example, see Figures S13 and S14, which are related to the Mw = 7.3 China earthquake that occurred on 21 May 2021 (Earthquake number 762 in Table S1). In Figure S13, an anomaly was detected 8 days before the earthquake that occurred at a distance of 992 km on track number 42010 of the SW-C satellite for 37 s in the Z component of the magnetic field. In Figure S14, an anomaly was detected 1 day before the occurrence of the same earthquake at a distance of 833 km in track number 42117 of the SW-C satellite. The anomaly was recorded for 60 s. As we can see, despite the fact that the distance of both orbits to the epicenter of the earthquake does not differ significantly, track 42117, which experienced an earthquake one day prior, exhibits the anomaly for a longer duration. Therefore, the effect of time on the duration of the anomaly can be shown in Figure S7. The x-axis is the earthquake’s magnitude, and the y-axis is the natural logarithm duration of the anomaly in time. According to Figure S7a, plotted for all the data, there is a natural logarithmic relationship between magnitude $M$ and duration $Du$ in seconds as follows:

$$ M = (1.449 \pm 0.918) \times \ln(Du \times Time) + (-1.113 \pm 0.739) $$  \hspace{1cm} (5)$$

where $Time$ is the time in days before the earthquake. The R-square of the system is also equal to 0.89, and the error value is equal to 0.256. In Figure S7b, the effect of geomagnetic indicators on the system is investigated. As observed, the stability of the system (R-square = 0.78) and the error values (R-mse = 0.35) have been somewhat affected, and this could be due to the limited time period we considered before the earthquake (only 10 days). Another test was performed on the system (Figure S7c,d) in which the signal-to-noise ratio for values higher than two (Figure S7c) and values higher than five (Figure S7d) is applied to the data. As observed, the error rate increases (R-mse = 0.32), and the system’s stability
decreases (R-square = 0.84). As mentioned earlier, this could be due to the limited time interval that was considered before each earthquake.

In particular, once a satellite anomaly is identified, Equations (2)–(5) allow for the estimation of three crucial precursor parameters, i.e., time, distance, and magnitude. These estimations are made possible through the measurement of anomaly duration, amplitude (“energy”), and distance of satellite data from the impending earthquake epicenter. We recognize that identifying a precursor alone does not provide full confidence in predicting earthquake occurrences, as the region of the event would require multiple precursors for a more reliable assessment [19,49]. However, we will show that the established correlations between some anomaly features and earthquake magnitude can serve as the base for an OEPS. We will not exclude that the next valuable outcome in precursor discussions could be a key component in future multi-parameter methodologies for an improved earthquake prediction method when including satellite magnetic field measurements.

3.1. Confutation Analysis

To verify that the observed magnetic anomalies are related to seismic activity in the region and not coincidental, a type of analysis called “confutation analysis” is performed, comparing the results from our real data analysis with the results from a synthetic data analysis [42].

Confutation analysis can aid in identifying and determining the causal relationship between magnetic anomalies and earthquakes. By manipulating the data in terms of time or location, we can gather more information about the actual correlation between these two phenomena. Confutation analysis allows us to investigate whether magnetic anomalies and earthquakes occur simultaneously in a specific location by chance or if there exists a direct causal relationship between them. This analysis can provide stronger evidence of the dependency between magnetic anomalies and seismic events or confute the results.

In this study, we cannot utilize temporal displacement because the entire Alpine–Himalayan seismic belt is considered (Figure 1), which is one of the three major seismic belts in the world. Essentially, it is not possible to find a time period within this belt that is fully free of earthquakes. Additionally, there is a limitation in the available data, as the data only cover the period from 2014 onwards. Therefore, for this confutation analysis, we cannot rely on temporal displacement.

In that case, we can only shift the data (E-W or N-S) laterally, which presents its own set of challenges. As a large region is considered in this context, it becomes challenging to displace this area to a location where no earthquakes have occurred. Furthermore, excessive N-S displacement may potentially result in the creation of magnetic conjugate anomalies [29,50,51]. Considering these conditions, we will shift the data southward by 30 degrees of latitude. The region to which the data has been shifted, as indicated in Figure S8, except for the two marked areas with a blue plus sign, shows relatively low seismic activity from 2014 to 2023. In Figure S8, the region to which the data has been shifted is indicated by a dashed blue rectangle, and the reference baseline is marked by a solid black rectangle. The main earthquakes are represented by hollow red circles, and their shifted positions are indicated by orange stars. On the other hand, since we have considered the Dobrovolsky region for earthquakes (Equation (1)), there may be some overlap in the case of major earthquakes. With all these considerations, it is indeed certain that the real seismic activity in the region to which the data has been shifted is lower than that of the Alpine–Himalayan seismic belt. Finally, applying the algorithm to the shifted synthetic earthquake data and real satellite measurements has yielded interesting results. Please note that the total number of earthquakes reduced slightly from 1077 to 1069 because some orbits did not cross a few corresponding Dobrovolsky regions. As shown in Table 3, without considering the constraints of geomagnetic indices and for all earthquakes with at least one abnormal orbit, only 256 out of 1069 earthquakes have exhibited pre-earthquake anomalies. This accounts for 24% of all earthquakes, whereas the ratio for the original earthquakes and magnetic field data is 83%. In the case where geomagnetic indices are
considered, as indicated in Table 4, for the shifted data, the percentage of earthquakes exhibiting precursors reduces to 17%, while for the original data, it is 78%. Based on the results, it can be concluded that the satellite observations of magnetic anomalies along the Alpine–Himalayan belt are not statistically random and could be related to the occurrence of earthquakes.

Table 3. The number of earthquakes in the base and shift regions regardless of geomagnetic conditions, and the percentage of earthquakes that had anomalies in both the baseline and shifted regions.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Number of EQs That Exhibit Anomalies</th>
<th>Total Number of EQs</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>900</td>
<td>1076</td>
<td>83</td>
</tr>
<tr>
<td>Shift</td>
<td>256</td>
<td>1069</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 4. The number of earthquakes in the base and shift regions considering the geomagnetic conditions that had anomalies in both the baseline and shifted regions, considering quiet geomagnetic conditions.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Number of EQs That Exhibit Anomalies</th>
<th>Total Number of EQs</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>615</td>
<td>786</td>
<td>78</td>
</tr>
<tr>
<td>Shift</td>
<td>132</td>
<td>770</td>
<td>17</td>
</tr>
</tbody>
</table>

3.2. Extended Validation Analyses as the Base for an OEPS

In this section, a more comprehensive analysis is conducted to depict the balance between success rate and false alarm rate [52–55]. For this reason, the results have been statistically analyzed based on the confusion matrix and relevant statistical metrics that have been measured [53]. In this analysis, we consider the number of orbits examined in each region on a daily basis. For a more rapid and realistic analysis, we did not consider geomagnetic indices (they need some time to be estimated from the World Centers, so they would not be quickly available for real-time analysis). Specifically, if an orbit shows an anomaly and an earthquake occurs within the range of that anomaly within the next 10 days, it is classified as a true positive. If no earthquake occurs, it is classified as a false positive. If no orbits indicate any anomalies, then a radius of 300 km will be considered as the effective earthquake distance and searched for the next 10 days. The choice of 300 km is an optimal conservative compromise with respect to a normally larger Dobrovolsky region (which happens when M ≥ 5.8). If no earthquake occurs within this radius, it will be classified as a true negative. If an earthquake does occur, it will be classified as a false negative.

The elements of the confusion matrix are completed according to Figure 4, and, on the basis of Table 5, we evaluate the following statistical quantities (e.g., [53]): accuracy, \( A = 79\% \); precision, \( P = 88\% \); hit rate, \( H = 84\% \); F1-score, \( F1 = 86\% \); and false alarm rate, \( F = 36\% \).

As evident, the confusion matrix demonstrates very high accuracy, precision, F1-score, and hit rate. These results are outstanding; they significantly surpass those obtained by recent works (e.g., [52,53]). However, there is a false alarm rate of 36%, which is not negligible, so the results found for real-time earthquake prediction should be used with great care. In that case, we would suggest some further actions to improve the OEPS and reduce the false alarm rate as much as possible.

The first two actions will be performed in the satellite anomaly identification. First, we can avoid moments with significant disturbed geomagnetic activity. This will exclude potential false anomalies, due to the solar wind and magnetosphere-ionosphere interaction instead of the preparatory phase of earthquakes. Secondly, we can check for repetition of anomalies in subsequent orbits: only those showing some minimal repetition will be taken.
Figure 4. Confusion matrix (at left) and common calculated performance metrics (at right) (e.g., [53]). TP = true positives; FP = false positives; FN = false negatives; TN = true negatives.

Table 5. Confusion matrix for the pre-earthquake anomaly detection as obtained from the time series analysis of magnetic field components. Y and N stand for positive (Yes) or negative (No) occurrence of seismicity or magnetic field anomalies.

<table>
<thead>
<tr>
<th>Bx, By, Bz Anomalies</th>
<th>Seismicity</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>5699</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1126</td>
<td>1427</td>
<td></td>
</tr>
<tr>
<td>Column totals</td>
<td>6825</td>
<td>2227</td>
<td></td>
</tr>
</tbody>
</table>

The other two actions can be undertaken after the anomaly identification. Thirdly, we look for consistency in the estimated magnitude among the different equations deduced from duration or energy, say within 0.5 magnitude units. Fourth, we can finally integrate this method with the analysis of other kinds of precursors, such as ground, atmospheric, and other kinds of ionospheric precursors [49], in order to improve the reliability of the OEPS as much as possible.

4. Conclusions

Between 2014 and 2023, focusing on M5.0+ earthquakes along the Alpine–Himalayan tectonic belt, we specifically analyzed 1077 earthquakes in the preceding 10-day period. Each earthquake underwent magnetic field signal analysis from the lower-orbit Swarm satellites, i.e., Alpha and Charlie, covering the 10 days preceding each earthquake event. Our scrutiny identified anomalies meeting predetermined anomaly criteria. Subsequently, our findings revealed a statistically significant correlation between earthquake magnitude and the duration and amplitude (“energy”) of the identified anomaly. Similar correlations were found also for other anomaly parameters, including the distance between the satellite anomaly and the earthquake epicenter.

To ensure the robustness of our results, a confutation analysis was conducted. In this analysis, when earthquake epicenters were displaced in latitude from their original positions, many less real satellite anomalies were detected and no significant correlation was observed between earthquake magnitude and the duration and amplitude of the chosen anomaly. This result reinforces the validity of our actual findings and refutes the possibility that they are merely the outcome of random chance. Finally, we also wanted to establish the degree of capability of the method to make predictions, so as to become the base for an OEPS: the high values of the accuracy and of the hit rate are indeed encouraging. However, the still non-negligible value of the false alarm rate suggests some caution before
applying the method to real-time earthquake prediction. Another limitation is that the prediction of large-magnitude earthquakes has a large spatial uncertainty, related to the large corresponding Dobrovolsky region. Some indications have been given to improving satellite anomaly identification, reducing the false alarm rate as much as possible, and integrating analysis of the satellite data with other data from the ground, atmosphere, and ionosphere [19,49].

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/10.3390/rs16162985/s1, Figures S1–S14; Table S1.

**Author Contributions:** H.R. was responsible for designing and organizing the work, conducting some data analyses, creating certain figures, and editing the final version. H.A. participated in searching the bibliography, performing data analyses, preparing some figures, and writing the first draft of the article. A.D.S. contributed to the organization of the work and the analysis process, validating the results, and reviewing, editing, and finalizing the article’s text to conform with the referee and editor requirements. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** Publicly available datasets were analyzed in this study. These data can be found in the USGS Seismic Catalogue and ESA Swarm data portals.

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**Conflicts of Interest:** The authors declare that they have no competing interests.

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